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EFFECTS OF OCEAN ENVIRONMENT (UNDERWATER)

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EFFECTS OF OCEAN ENVIRONMENT (UNDERWATER) * †

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The first question which must be addressed in a paper entitled "Effects of Ocean Environment (Underwater)" is "Effects on what?" The outline of the general classes of systems which might be considered are shown on the first four slides. These systems are Physical Systems, Biological Systems, Geophysical Systems and, lastly, Economic and Social Systems. These slides do not purport to represent the totality of systems that might be affected by the underwater ocean environment. They are only intended to be a list of some of the more obvious effects which might be considered.

For example, I have purposefully omitted the effect of the underwater environment on the evolutionary history of biological organisms. Lack of time will clearly prohibit a discussion of such delightful topics as the causal relationship between the spectral response of the human eye and the transmission of electromagnetic energy through sea water.

The list shown in these first four slides is a rather mundane list and is limited to fairly prosaic items. A detailed treatment of any one of these subjects, or even sub-headings, would require an extended course of lectures.

In an attempt to complete a talk within the limits of allotted time, I shall particularize the discussion to the subject matter of the first slide.

PHYSICAL SYSTEMS

STRUCTURES

DYNAMIC AND STATIC FORCES
CORROSION
BURIAL
ATTACK BY MARINE ORGANISMS

ENERGY TRANSMISSION SYSTEMS

ACOUSTIC
ELECTROMAGNETIC

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BIOLOGICAL SYSTEMS

MARINE ORGANISMS

ECOLOGICAL CYCLES

MIGRATION PATTERNS

DIURNAL

SEASONAL

GEOGRAPHIC

HUMAN ORGANISMS

LIMITATIONS ON
MAN IN THE SEA

GEOPHYSICAL SYSTEMS

PRECIPITATION OF PARTICULATE MATTER

LENS AND LAYER FORMATION

TURBIDITY CURRENTS

ECONOMIC AND SOCIAL SYSTEMS

UNDERSEA WARFARE

MINING

FOOD RESOURCES

OIL AND GAS RECOVERY

RECREATION

I have rather arbitrarily divided Physical Systems into two categories. These are Structures and Energy Transmission Systems.

In designing structures for underwater service, the first fact to be considered is that the ocean environment is, to a first approximation, described by a number of very obvious characteristics. The first of these is the fact that the ocean is composed of a substance called "sea water," whose outstanding characteristic is its great density relative to air. For the normal ranges of temperatures and pressures encountered in both the ocean and atmospheres, sea water is approximately 800 times as dense as air at standard atmospheric pressure. Furthermore, the viscosity of sea water is about 10^{-2} Poise, which is about 55 times larger than the viscosity of the atmosphere.

As a general consequence of these factors, the static and buoyant forces encountered in the ocean are usually very large. It is generally known that the static pressure increases at a rate of approximately 44 pounds per square inch per 100 feet of additional depth. Thus, at a depth of 20,000 feet in the ocean, the static pressure on any body immersed in the ocean is approximately 8800 pounds per square inch. Indeed, there are places in the ocean that are deep enough so that the static pressure will be as great as 15,000 pounds per square inch. Clearly, any structure which is designed to operate at these depths must be made to withstand significant pressures.

While most people appreciate the magnitude of such static pressures, a few other consequences of these pressures are generally overlooked. Most metals have a temperature where a phase transition from the brittle to the

ductile form occurs. This is particularly true in alloys. Furthermore, the temperature at which such a transition occurs is pressure dependent. Pressures of the order of 10,000 psi can reduce the transition temperature for some metals by as much as 50 degrees. Such transitions normally cause certain rearrangements of the material and, where the metal has well defined internal grain boundaries, the effects of many pressure cycles are cumulative. The material, after being subject to such high static pressures, does not return to its original properties. Thus, metals and alloys that are used for deep water environments must be selected with great care. For those of you who are interested in this problem, there have been a series of rather interesting studies that have been published by Dr. Alan Johnson and his group at Brooklyn Polytechnic Institute.

In addition to the static compressive forces generated in the deep ocean environment, significant buoyant forces also exist. While buoyancy has been appreciated since the time of Archimedes, it is worth pointing out the magnitude of such forces. A buoyant force of 64 pounds is generated for every cubic foot of displaced sea water. Thus, an object with a relatively modest external volume that amounts to, say, 100 cubic feet, will be subject to buoyant forces of 6400 pounds. Despite the fact that buoyant forces of considerable magnitude are exerted on any body immersed in the sea, it is often difficult to design a structure which will survive at very great depths and still have a net positive buoyancy. The compressive forces, which must be counteracted, are often sufficient to cause one to arrive at a design such that

STOKES LAW

$$V_t = \frac{2r^2(\rho - \rho^1)g}{9\eta}$$

IN AIR

$r = .1$ cm

$\eta = 1.8 \times 10^{-4}$

$\rho = 8$

$\rho^1 = 0$

$V_t = 1 \times 10^5$ cm/sec

IN WATER

$r = .1$ cm

$\eta = 1 \times 10^{-2}$

$\rho = 8$

$\rho^1 = 1$

$V_t = 1.5 \times 10^3$ cm/sec

$$D = \frac{C_D V^2 A}{2}$$

WHERE: C_D = DRAG COEFFICIENT

V = RELATIVE VELOCITY

A = PROJECTED AREA

the weight of the shell necessary to satisfy pressure requirements far exceeds any buoyant force. Fortunately, considerable ingenuity has been manifest in recent years by designers of deep sea equipment. As a result, a remarkable series of structures have been designed, using materials such as glass for pressure vessels. It is quite possible to design a glass sphere having an internal void amounting to approximately 90% of the total volume and a net buoyancy of 20 or 30 pounds. Such a sphere is capable of withstanding terminal pressures of 10,000 pounds per square inch. It appears that when large amounts of net buoyancy are required for deep ocean use, the most expedient design involves the iteration of many small hollow spheres composed of a material, such as glass, which has a high compressive strength to weight ratio.

In addition to the large static and buoyant forces which are encountered under water, dynamic forces of significant magnitude can also be encountered with very small stream velocities. A few elementary calculations will serve to establish the relative magnitudes. For example, the terminal velocity of a small sphere falling in a fluid is given by Stokes' Law, which is shown in the next slide. A comparison for air and water for spheres .1 cm in diameter is shown. The terminal velocity of such a sphere in water of 20° C is about 15 meters/sec while it is 1000 meters/sec in air.

Put in other terms, the drag on a flat plate, immersed in a water current of small magnitude is shown on the next slide.

Suppose we had a body with a relatively low drag coefficient of unity and a projected area of 5 square feet. If we wanted to move this body through air at 60 miles per hour, we would require a total force of only 46 pounds and we

would require a propulsion power of 8 horsepower. If, on the other hand, we wished to move this body at 60 miles per hour through water, we would require a total force of about 19,400 pounds and a propulsion power of 3200 horsepower. The difference is impressively great.

Indeed, the drag forces in water are significantly large even for small currents. If you have any doubts concerning the validity of this assertion, consider the classic problem of the taut wire mooring. Suppose that we wanted to hold a 1 inch diameter, 12,000 foot long wire, vertical in an ocean current. For a uniform horizontal current of 1 knot, the total side force would be about 1 ton. The wire could, in principle, be held reasonably vertical by applying a sufficient vertical force. If our objective was verticality to within, say, 1/2 degree, then a vertical force of 200,000 pounds would be required. Since this would be sufficient to break most cables of 1 inch diameter, it is unlikely that we would achieve our objectives in a 1 knot current.

Current forces are not only large, but vary in both magnitude and direction. Any underwater structure is, thus, subjected to dynamic forces which tend to set up vibration and induce changing internal stresses on structural members. Normally, oceanographic structures are sufficiently overdesigned that such dynamic stresses can be disregarded. There are, however, structures such as buoyed up cable systems where the factor of safety is not very large. In vertical cable systems the dynamic stressing of cables tends to produce brittleness. Eventually, this cold working of the cables, together with stress corrosion, causes cable failure. There is no simple or obvious

way of avoiding dynamic stresses in the ocean. The best a designer can do is to attempt to incorporate a sufficiently large factor of safety so as to relegate the dynamic forces to the level of a relatively insignificant component of the total forces encountered.

Aside from the fact that the ocean is composed of water, its second most obvious characteristic is that this water is not fresh water. It contains, as shown in the next slide, a majority of the known elements. Of the dissolved material, the most abundant component is the chloride ion which amounts to 55% of the total. A significant feature of sea water is that while the total concentration of dissolved salts may vary from place to place, the ratio of the most abundant components remains almost constant. Such a complicated solution of electrolytes will, of course, have rather strong effects on any foreign body introduced into sea water. Indeed, it has long been recognized that one of the principal environmental effects of the ocean is corrosion of any unprotected metallic substance inserted in the sea.

Corrosion can be considered as the reversion of refined metals to a more natural state. With the exception of certain man-made environments, such as chemical plants, for example, this reversion can occur more quickly and with more disastrous results in or near the ocean than anywhere else on earth. The study of corrosion is a complex, semi-empirical science. Much has been learned through years of experimenting, testing and theoretical study. Much remains to be learned, however, and many of the processes that are recognized are poorly understood. It is obvious, therefore, that the

GEOCHEMICAL PARAMETERS OF SEA-WATER

Element	Abundance, mg/l.	Residence time, years
H	108,000	
He	0.000005	
Li	0.17	2.0×10^7
Be	0.0000006	1.5×10^2
B	4.6	
C	28	
N	0.5	
O	857,000	
F	1.3	
Ne	0.0001	
Na	10,500	2.6×10^8
Mg	1,350	4.5×10^7
Al	0.01	1.0×10^2
Si	3	5.0×10^3
P	0.07	
S	885	
Cl	10,000	
A	0.6	
K	380	1.1×10^7
Ca	400	5.0×10^6
Sc	0.00004	5.6×10^2
Ti	0.001	1.6×10^4
V	0.002	1.0×10^4
Cr	0.00005	3.5×10^2
Mn	0.002	1.4×10^3
Fe	0.01	1.4×10^2
Co	0.0005	1.8×10^4
Ni	0.002	1.8×10^4
Cu	0.003	5.0×10^4
Zn	0.01	1.8×10^5
Ga	0.00003	1.4×10^3
Ge	0.00007	7.0×10^3
As	0.003	
Se	0.004	
Br	65	
Kr	0.0003	
Rb	0.12	2.7×10^5
Sr	8	1.9×10^7
Y	0.0003	7.5×10^3
Zr		
Nb	0.00001	3.0×10^2
Mo	0.01	5.0×10^3
Tc		
Ru		
Rh		
Pd		
Ag	0.0003	2.1×10^6
Cd	0.00011	5.0×10^5
In	<0.02	
Sn	0.003	5.0×10^5
Sb	0.0005	3.5×10^5
Te		
I	0.06	
Xe	0.0001	
Cs	0.0005	4.0×10^4
Ba	0.03	8.4×10^4
La	0.0003	1.1×10^4
Ce	0.0004	6.1×10^3
W	0.0001	
Re		
Os		
Ir		
Pt		
Au	0.000004	5.6×10^5
Hg	0.00003	4.2×10^4
Tl	<0.00001	
Pb	0.00003	2.0×10^3
Bi	0.00002	4.5×10^5
Po		
At	0.6×10^{-15}	
Rn		
Fr		
Ra	1.0×10^{-10}	
Ac		
Th	0.00005	3.5×10^2
Pa	2.0×10^{-9}	
U	0.003	5.0×10^3

oceanographic engineers should avail themselves as much as possible of what is known before designing for the ocean environment. While I don't intend to produce a treatise here on the science of corrosion, a few of the problem areas as they affect ocean systems must be considered.

Corrosion is, of course, an electrochemical phenomenon. For it to occur, three basic conditions are necessary. First, there must be an electrolyte. Sea water qualifies extremely well, containing as it does not only hydrogen and hydroxyl ions, but over 40 natural elements, both in combination and in their natural state, in easily detectable amounts. It also contains dissolved hydrogen, oxygen, nitrogen, carbon dioxide, and all the ions that result from their many chemical combinations. Not only do the amounts of these materials vary with ocean depth and geographical location, but local differential concentrations can result from hydrodynamic stagnation, organic action, and the corrosion process itself. The second requirement is that there must be two electrodes that display a mutual potential difference when placed in the electrolyte. These electrodes must be made of two different metals or alloys of the same metal or merely different areas of the same piece of metal. The more positive electrode is, of course, called the cathode and the other the anode. The deterioration area is almost always the anode. The final requirement for corrosion is the need for a closed electric circuit. For galvanic action to occur, a metallic path must exist between the cathode and the anode.

There are many factors effecting corrosion and since each varies under specific conditions of use, it is not possible to say that any one is more important than any other. In simple terms, galvanic corrosion is the accelerated effect produced when the metallic connection is provided. This connection may be macroscopic, as when one major structure is attached to another, or it may be microscopic, as between grain boundaries in the surface of an alloy. The analogy with a flashlight battery is direct. Unused, its charge may dribble away gradually over a long period of time. If a low resistance path is placed between the terminals, its life is catastrophically short.

The factors which determine the seriousness of the corrosion problem in the ocean environment are more meaningful when divided into two groups. The first group includes factors over which one may have control, while the second group includes those over which we have no control. The most obvious factor in which man has no control are the characteristics of the environment in which he must work, namely, the ocean itself. Closely allied to this are the imposed conditions of just what it is the system must do in the ocean - that is, sit on the bottom, float on the bottom, be towed through the water, etc., and for how long. While environmental factors may not be constant throughout the ocean, they are, none the less, present and in a given location virtually unalterable. In some cases these factors can be determined precisely, both quantitatively and qualitatively. More often they cannot, and if the engineer does not know the precise values of his particular situation, he

must design for the worst.   In general, the salinity varies only slightly from 3-1/2 percent.   Sea water is basic with a pH ranging generally between 7. 8 and 8. 4.   The oxygen content, which is extremely important in some corrosion problems, can and does vary from zero to a saturation value that is nearly 10 milliliters, for low salinities and temperatures.   Anaerobic conditions exist in some areas and even hydrogen sulphide can be present in the water as well as in the bottom sediments.   This is often true in the deep stagnant holes characteristic of most Norwegian fjords and some estuaries. The salinity of sea water is a major factor in determining the potential difference between metals immersed in it.   These potentials also vary, however, according to parameters over which an oceanographic engineer has little or no control.   The temperature of the sea water varies typically between -2 degrees C and +32 degrees C.   With the exception of the polar regions, the coldest water is usually found in the deep ocean, while the warmest water is at or near the surface above the thermocline.

For the most part, corrosion proceeds most rapidly under warmer conditions.   The speed of natural currents in the ocean varies from zero to upwards of 5 knots.   Some equipment, of course, is designed to be towed at speeds of up to 60 knots.   Among the natural currents, the highest speeds are almost always found at the ocean surface.   Currents along the floor of the deep ocean may be as low as a few feet per year.   Turbulence can vary over a wide range.   Little is known about either the scale or energy of turbulence in the ocean, although its effect on corrosion is well established.   The

duration of immersion of any physical system will appreciably affect the

measured potentials of some alloys, although the effect of time generally

is lessened if the water velocities are high.

All of the factors enumerated above have some effect on the potentials

measured between metals and the sea water electrolytes.   The table, Gal-

vanic Series of Metals and Alloys in Sea Water, is shown in the next slide.

This shows the relative potentials for a given set of environmental conditions,

i. e., in running sea water with a velocity of 13 feet per second and an average

sea water temperature ranging from 24 degrees C to 27 degrees C.   These

data were prepared by the Development & Research Division of the Inter-

national Nickel Company, Inc., Wrightsville Beach, North Carolina, which

is the home of International Nickel Company's Sea Horse Institute.   One must

observe the caution that these are the potentials under these conditions only

and should not be used interchangeably with potentials used under other con-

ditions.

At the risk of appearing silly, I point out that one should not purposely

design underwater systems where two metals with significantly different poten-

tials will be in contact.   One shouldn't, but occasionally it is done with

predictably deplorable results.   This caution extends also to those in the

field who might be inclined to hang paraphernalia on a system without taking

this factor into consideration.

A certain amount of witchcraft is involved in corrosion.   For example,

while aluminum occupies a relatively lowly position in the galvanic series, it

GALVANIC SERIES OF METALS AND ALLOYS IN SEA WATER

Sea Water Velocity: 13 feet per second.

Material	Potential -Volts*
corroded end (anodic or least noble)	
Zinc	1.03
Alclad 3SH	0.94
Aluminum 3SH	0.79
Aluminum 61ST	0.76
Aluminum 63ST	0.75
Aluminum 52SH	0.74
2% Ni Cast Iron	0.68
Cast Iron	0.61
Carbon Steel	0.61
Cor-Ten	0.6
Type 430 Active	0.57
Ni-Resist Type II	0.54
Type 304 Active	0.53
Type 410 Active	0.52
Ni-Resist Type III	0.49
Ni-Resist Type IV	0.48
Ni-Resist Type I	0.46
Tobin Bronze	0.40
Yellow Brass	0.36
Copper	0.36
Red Brass	0.33
Aluminum Brass	0.32
Composition "G" Bronze	0.31
Admiralty Brass	0.29
90-10 Cu-Ni + .82 Fe	0.28
70-30 Cu-Ni + .06 Fe	0.27
70-30 Cu-Ni + .45 Fe	0.25
Type 430 Passive	0.22
"A" Nickel	0.20
Type 316 Active	0.18
Inconel	0.17
Type 410 Passive	0.15
PDA Titanium	0.15
Silver	0.13
BI Titanium	0.1
Type 304 Passive	0.084
Hastelloy "C"	0.079
Monel	0.075
Type 316 Passive	0.05

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is important to remember that different alloys of the same metal can behave differently. This is currently believed to be related to the purity of the base metal that goes into the alloy. Also, the corrosion rates for some aluminum alloys are inversely proportional to the amount of dissolved oxygen present. Other factors which affect corrosive attack on aluminum include cavitation, crevice corrosion, deposition attack, intergranular corrosion, pitting, stress corrosion cracking, and, of course, the types of coating systems used.

Biological fouling can contribute to corrosion in many ways. Metabolic by-products include acids, carbon dioxide, ammonia, hydrogen sulphide and others which may be intrinsically corrosive and may act as catalysts or depolarizers. The presence of organisms may also cause local stagnation, thus encouraging the initiation of differential oxygen cells. In still other instances, this may cause otherwise protective coatings to be breached with a subsequent onset of corrosion. The nature and extent of creature damage varies sharply, as we shall see later, with geographic location, season, and location in the water column.

While we are on the subject of marine organisms, it is appropriate to note that one of the major elements of the underwater environment with which a physical system must always contend is the presence of biological action. Anyone who has even seen a dock or the bottom of a ship has seen marine growth and is vaguely aware of the fact that such growth is, on occasion, destructive. However, while most people are aware of the problem, few people who normally do not deal with the underwater environment are aware of the magnitude of the problem. In a period of six to eight months

at sea a ship may acquire a growth of barnacles of from two to three inches thick, weighing more than 100 tons. This weighty crust can cut the ship's speed by 10 percent or more and require a 50 percent increase in fuel consumption to keep it on schedule. That is an awful lot of fuel, when you consider that a big ship uses about a ton of fuel a minute. Added fuel costs are only part of the financial drain caused by barnacles. The creatures can get so firmly attached to a ship's bottom that sometimes a jackhammer is needed to scrape the hull clean. Ridding a ship of its population of barnacles usually means that the ship must be drydocked. To dock, scrape, and re-paint the hull of a superliner, like the United States, would cost more than 75 thousand dollars, not counting the loss of service.

The U. S. Navy estimates that dealing with barnacles on its ships costs the U. S. taxpayers 280 million dollars a year, not including the loss of the service of the ships. Removing these animals is absolutely necessary. On a Naval warship a fouled bottom, as a barnacled hull is called, can mean the loss of speed that might spell a military defeat. Furthermore, if the barnacles are not removed, they will continue to collect indefinitely, settling one on top of another until very thick accretions are made.

Ancient as the problem is, the battle against the barnacle has been waged with only limited success over the centuries. The Phoenicians and the Carthaginians are believed to have used pitch and possibly copper sheathing on their wooden ships' bottoms to prevent fouling. In later centuries, other shipbuilders tried various paints, lead, zinc, arsenic, mercury, acids, and

even ground glass to discourage barnacles and other clinging sea creatures.

Copper sheathing worked well on wooden ships because copper is highly

poisonous to fouling organisms.   However, with the advent of iron hulls,

copper could not be used because the proximity of the copper and iron would

result in a chemical reaction that tended to eat away the ship's hull.   In the

mid-nineteenth century anti-fouling paints containing copper oxide came into

widespread use and to this day are the main weapons against barnacles.   Even

now, the best anti-fouling paints last for only about two years.   After that

most of the copper in the paint has been leached out and the barnacles begin

to accumulate again.

In addition to the obvious biological problem presented to ships and

piers by barnacles, other physical systems imbedded in the sea suffer bio-

logical deterioration.   One of the earliest systems to run into the problem of

biological attack by marine organisms was underwater telegraph cables.   It

was discovered quite early in the process of cable laying that teredos just

loved telegraph cables and would promptly destroy them.   The first counter-

measure that was adopted was to coat the cables with a thin sheet of brass

which was wound in a spiral layer completely around the wire.   This very

expensive and heavy-handed solution continues to be incorporated in the

design of all submarine cables used today.   All submarine cables contain

teredo protection, whether they are used in shallow tropical water or in deep

arctic waters.   The brass sheet is there whether or not the teredos are or

are not present.   Submarine cable designers are a conservative lot and don't

like to take chances with the underwater environment.

A more rational approach to the problem is gradually being dis-
covered by our R&D community.   The first systematic assault on the
problem of biological destruction in the ocean has been sponsored by the U. S.
Navy. Until recently the precise distribution and the relative susceptibility
of different materials to biological deterioration in the underwater environ-
ment was not known with regard to such parameters as depth, geographic
location, etc.   In 1962 a series of 6 submersible test units were placed on
various depths on the ocean floor at a number of locations off the coast of
California.   The first of these test units was loaded with 1,367 test specimens
containing 492 different materials. Later test units were loaded with as many
as 2400 specimens containing 603 distinct materials.   Concurrently with the
submersible test unit program, numerous oceanographic and biological data -
collecting cruises to the submersible test unit sites were conducted.   These
produced information about environmental parameters such as salinity,
temperature, oxygen content, and biological activity.   This information was
essential in evaluating changes in material exposed on the ocean floor and
especially the corrosion of metals.

The majority of test specimens on the submersible test units were
metals and metal alloys which were used to study the effects of the deep ocean
environment on corrosion.   The major fouling organisms found attached to the
surface of metal specimens are a species of hydroids belonging to the phylum
coelentra.. (Next slide) Anywhere from a trace to a heavy hydroid growth
was found on all of the metal test specimens.   Some of the hydroids were

STU I-1

Stalked marine animal (hydroids) up to 2-1/2 inches long attached perpendicularly to the metal and plastic panel.
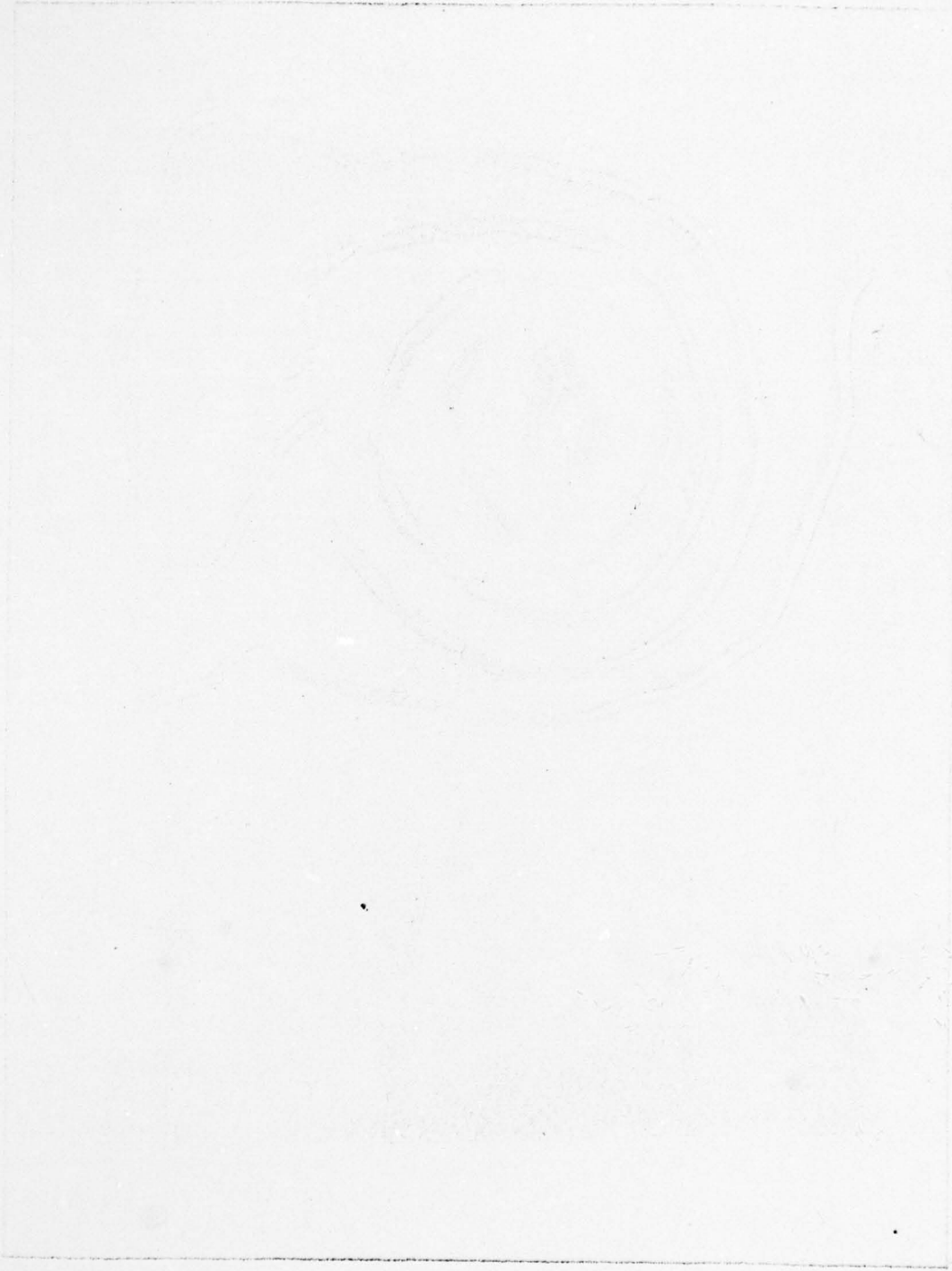
Spiraled white calcareous worm tube attached to the vinyl-painted metal specimen holder.

Serpulid tube worm on the surface of a Hastelloy C test panel.

3 to 4 inches long. The heaviest growth occurred on the surface of a No. 316 stainless steel specimen. Two different kinds of surpulid worm tubes constructed of different materials were found on the test panels. One of these tubes was made of white calcareous material which was hard and brittle. (Next slide) Several such tubes were found attached to the surface of stainless steel panels which were partially exposed to the sediment. (Next slide) Numerous stalked marine animals up to 2-1/2 inches long were attached perpendicularly to the surface of metal specimens. These organisms are also a species of hydroid.

Fouling organisms such as barnacles and bryozoa were not found on any of the deep test specimens. Barnacles were, of course, of special concern because pits could result from localized oxygen concentration cells formed on the surface of the metal under the barnacle growth.

Hydroid growth was found on all of the non-metal test specimens such as painted and coated panels and plastic and elastomer surfaces. A spiral tube worm was attached to a painted metal test specimen about 6 feet above the bottom. It is interesting to note that typical fouling organisms found in shallow waters, such as barnacles, tunicates and bryozoa were not observed on panels exposed at a depth of 6800 feet.

A total of 26 wood test panels which included pine, fir, ash, maple, cedar, oak and redwood were exposed for periods up to 36 months to determine the effects of deep sea animals on different woods. All wooden panels were attacked by marine borers and sustained light to heavy damage. (next slide)

Pine-wood panel riddled by borers. Top panel shows numerous shaft entrance and breathing holes. Bottom panel shows the interior of same wood.

Interior of wood completely riddled by borers. The shells of the molluscan borers are visible.

STU I-1

Pine-wood panel riddled by borers. The panels were
sandwiched between two metals.

Pine-wood panel riddled by borers. Top panel shows numerous small entrance and breathing holes. Bottom panel shows the interior of same wood.
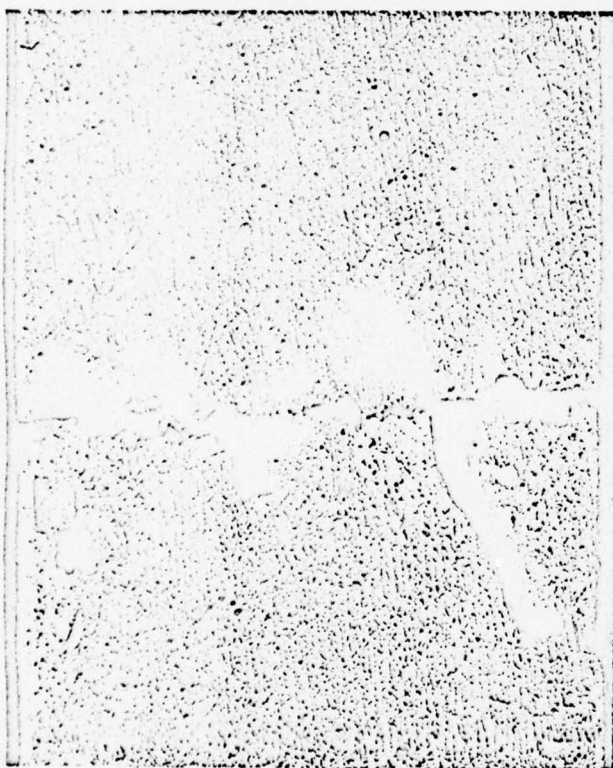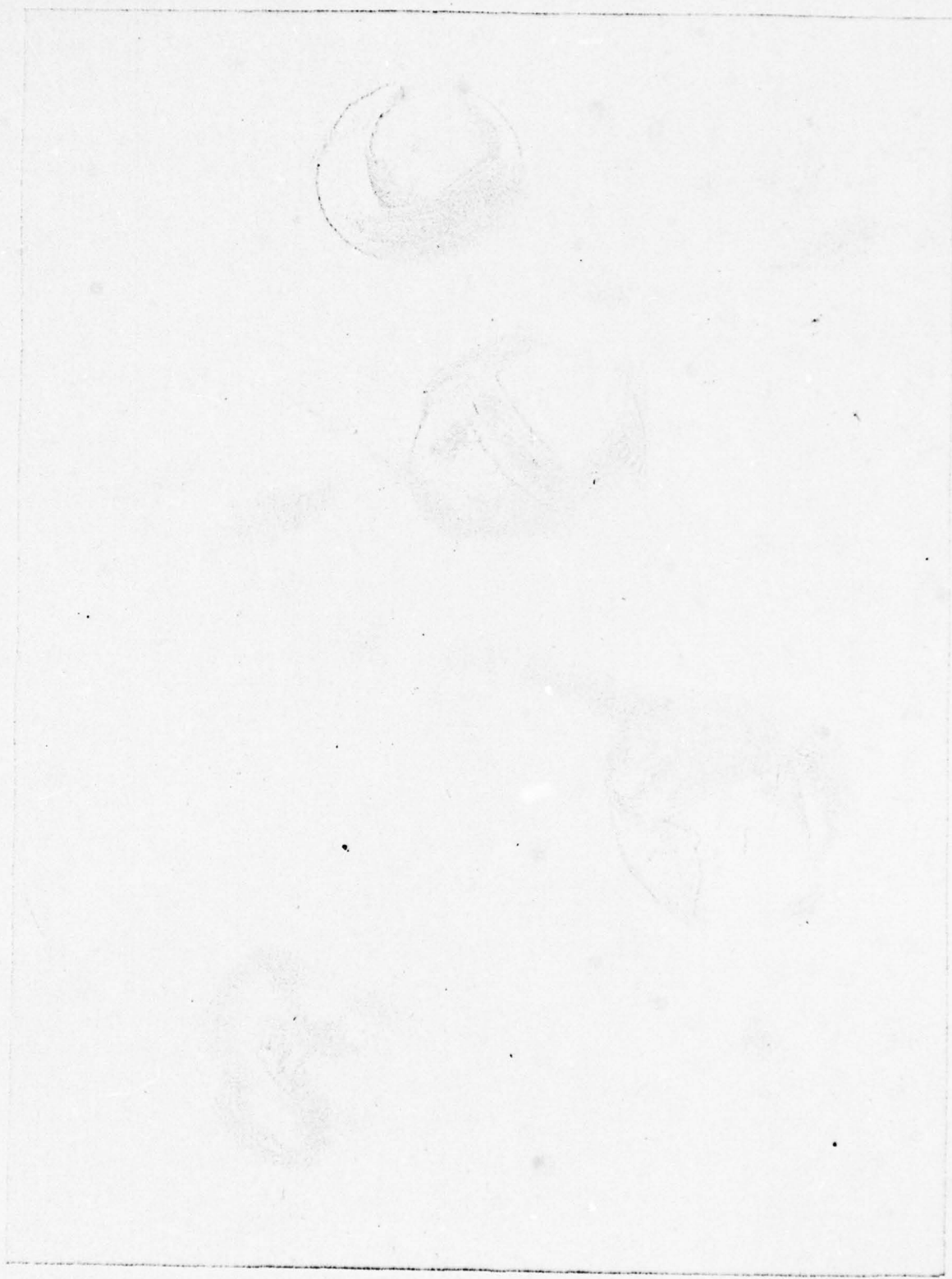
Closeup view of _Xylophaga_ sp.

The severest damage was sustained by cedar and oak; moderate damage was sustained by ash, pine, fir and maple; and light damage was sustained by redwood. .(Next slide)   The external sides of the panel exposed to sea water appeared to be relatively free of any borer attack.   However, when the wood panels were removed from the phenolic laminated plastic sheet and the sides attached to plastic sheets were examined, it became evident that the interior of the wood was completely riddled by marine borers.   A close-up of some of the culprits is shown in the next slide.   The majority of the borer tunnels measured about 5/16 inches in diameter.   The average borer tunnel in redwood measured about 1/8 inch in diameter.   Wood panels which were exposed about a half a foot above the sediment layer were much more severely damaged by the borers than the set of panels exposed three to four feet above the sediment layer.   This indicates that the deep sea marine borers are very active in large numbers immediately above the sediment layer and their number tends to decrease in sea water as the distance from the sediment layer increases.   It is possible, although it has not been verified, that these borers may not be present in sea water about 25 feet above the ocean floor.

The greatest borer population was found in the 2x4x30 pieces of untreated fir fitted over plastic rods and tubes.   Some borers about 3/16 of inch in diameter had penetrated about 1-1/2 inches into the center of the wood from the cut end.   Brownish fungi, hyphae, were detected in the wood.   A heavy growth of slime bacteria was present over the surface of cotton and manilla rope and a like growth of slime was present over the surface of nylon

Cotton rope deteriorated by bacterial action.

The 1/2-inch-diameter Manila rope deteriorated by the combined effects of microorganisms and borers. Two borers are visible.

and polypropylene ropes.   The fibers of cotton rope were decayed con-
siderably by bacterial action (next slide) and, as a result, were easily
pulled apart by tweezers.   When the cotton rope was handled after it had been
dried, the rope fibers crumbled into small pieces.   Only a few borers were
found on the surface of the cotton rope and none of these had bored into the
rope.   The 1/2 inch diameter manila rope specimens were severely damaged
by both borers and microorganisms.   (Next slide)   Borers ranging in size
from 1/32 to 1/8 inch diameter had completely infested the entire length of
the 5 foot long rope specimens.   Rope fibers were severed completely as
the borers penetrated into the rope.   The slime bacteria were responsible
for the decay and deterioration of the fiber materials.   Examination of the
nylon and polypropylene ropes under a stereoscopic camera microscope showed
that the fibers in these ropes were neither severed nor damaged by marine
borers.   On the contrary, the fibers were in excellent condition.   Some of
the plastic specimens tested fared quite well in a marine environment.   Others
did not.   It was found that lower sections exposed about a half a foot above the
sediment layer had more borer holes than upper sections exposed three feet
above the sediment.

The result can be summarized by saying that electrical cable insulation
composed of silicon rubber was deteriorated by the nibbling and biting action
of some marine animals.   The materials shown in the next slide were not
affected by marine organisms.   Two species of marine borer were found in
wood specimens and have been identified as xylophaga washingtona and
xylophaga duplicata.   The borers were responsible for the deterioration

MATERIALS NOT AFFECTED

BY MARINE ORGANISMS:

1. RUBBER VACUUM TUBING

2. NYLON BOLTS AND NUTS

3. NYLON AND POLYPROPYLENE ROPE

4. ETHYL CELLULOSE CABLE CLAMPS

5. NEOPRENE, BUTYL AND NATURAL
   RUBBER ELECTRICAL CABLE INSULATION

6. VARIOUS PLASTIC LAMINATED SHEETS

7. GLASS MICROSCOPE SLIDES

MATERIALS ATTACKED

BY XYLOPHAGA

1. PINE
2. CEDAR
3. OAK
4. MAPLE
5. ASH
6. REDWOOD
7. DERALIN
8. NYLON
9. POLYCARBONATE
10. TEFLON
11. CELLULOSE ACETATE
12. POLYETHYLENE
13. ACRYLICS
14. POLYSTYRENE
15. VINYL TUBES
16. MANILA ROPES

MATERIALS NOT SUSCEPTIBLE TO BIOLOGICAL DETERIORATION

1. RUBBER VACUUM TUBING
2. ACRYLIC SHEET
3. NYLON BOLTS AND NUTS
4. NYLON AND POLYPROPYLENE ROPE
5. ETHYL CELLULOSE CABLE CLAMPS
6. LAMINATED PLASTIC SHEETS
7. GLASS SLIDES
8. ELECTRICAL CABLE INSULATION COMPOSED OF NEOPRENE, BUTYL, OR NATURAL RUBBER
9. POLYVINYL CHLORIDE

MATERIAL SUSCEPTIBLE TO
TOTAL BIOLOGICAL DESTRUCTION

1. UNTREATED PINE
2. FIR
3. REDWOOD
4. CEDAR
5. ASH
6. OAK
7. MAPLE
8. MANILLA AND COTTON ROPES
9. BURLAP MADE OF JUTE FIBERS

of the material shown in the next slide. It may be concluded that the materials shown in the next slide are susceptible to total biological destruction and are not suitable for use in the deep ocean. While the tests are not conclusive, it appears that the materials shown in the next slide are probably not susceptible to biological deterioration in the underwater environment.

If you will recall for a moment our first slide, the last effect of the underwater environment on physical systems was burial. If you are unfamiliar with the deep ocean environment, the inclusion of this factor might be somewhat surprising. However, those of you who have ever thought seriously about the problem of recovering treasure from sunken pirate vessels are aware that one of the principal difficulties is that vessels which sank in shallow waters, even in relatively short historic times, are usually buried.

The burial may take one of two forms. There may be a precipitation of particulate matter on top of the structure or there may be a sufficient coral growth, in tropical waters at least, so that the total structure becomes buried under a hard cake of marine organisms. In shallow water the problem of burial is extremely serious. Near the mouths of major rivers vast quantities of sediment are continually transported out to sea. Thousands of tons of dissolved matter come out of the mouths of all of our major rivers. Fairly large objects, such as submerged military mines, can be buried in periods as short as 6 hours. Burials of objects 6 feet in diameter have been known to take place in the North Sea in periods as short as 12 hours. This form of burial presents a particularly difficult environmental hazard to most people

working with equipment at the bottom of the sea.

While we may neglect the military problems related to detection, localization and destruction of buried mines, a very real problem remains for people who lay marine cables, underwater pipe lines and other structures on the bottom of the sea. The weight of the material causing burial induces tensions in the buried structures that one normally does not design for. Slight earthquakes are usually enough to snap underwater cables if they are buried in a significant manner. Not all of the burial, incidentally, occurs precisely on continental shelves or near the mouths of rivers. Indeed, a classic case occurred some years ago when most of the trans-Atlantic cables were broken due to a large turbidity current which transported thousands of tons of material down the continental shelf and suddenly broke all cables between Newfoundland and England. The turbidity current was triggered by a deep-seated earthquake and succeeded in burying most of the ends of the cables. Fortunately, in most of the deep ocean basins, the process of burial is very, very slow. Indeed, in clear deep ocean basins it is estimated that particulate matter precipitates at a rate of only millimeters per century. Thus, if one does not have to cope with inshore areas, the problem of burial can be neglected.

In the first slide attention was drawn to the effect of the underwater environment on energy transmission systems. The two general types of systems to be considered include acoustic and electromagnetic transmission systems.

ABSORPTION AND SCATTERING COEFFICIENTS

	Distilled Water			Chesapeake Bay	
λ	σ	β		σ	β
4000 Å	3.4×10^{-4}	4.4×10^{-4}			
4500	2.25	1.7		19	37
5000	1.5	2.3		17	21
5500	1	3.7		18	14
6000	.7	19		18	25
6500	.5	30		18	34
7000	.4	57		18	56

σ is the part of the absorption of a light beam arising from scattering and β that due to pure absorption. The total absorption is given by $k = \sigma + \beta$ where k occurs in the exponential e^{-kx} with x in cm. Source: E. O. Hulburt, J. Opt. Soc. Am. <u>35</u>, 698 (1945).
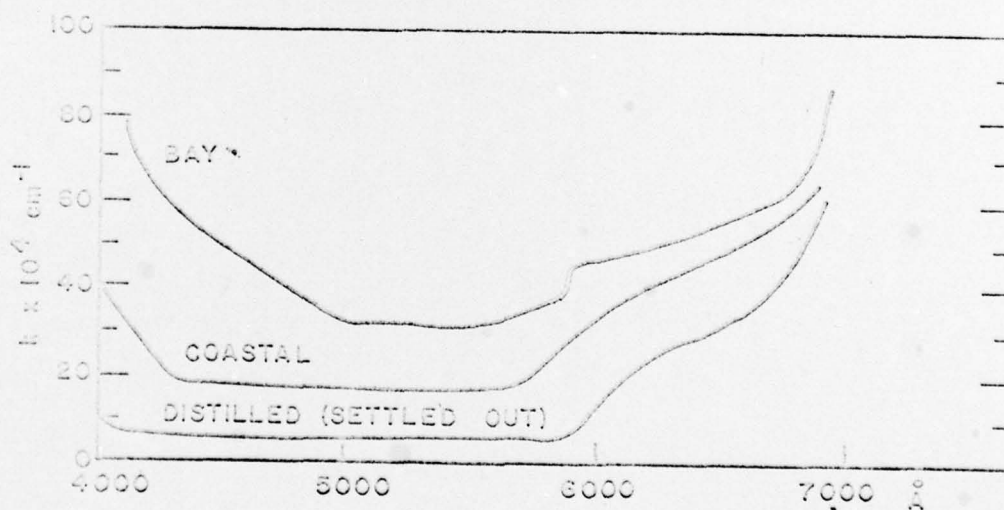
Electromagnetic systems are considered rather rapidly. The next slide shows the attenuation of electromagnetic energy in the visual band in sea water. We follow this with a slide showing the absorption of infrared in sea water. Clearly, electromagnetic energy cannot be transmitted very far in sea water. As a consequence, the undersea environment is a rather dark one. Systems such as TV cameras which attempt "to see" in the ocean are invariably short range systems. Even high intensity illumination systems do not allow one to see very far.

As a result of such inherent difficulties with electromagnetic energy, acoustic transmission systems assume vastly more importance.

In the ocean the essential parameter for acoustic studies is the velocity of sound, which is a complication function of depth and geography. Because of this, one often has to deal extensively with the inverse problem of determining the appropriate model by acoustic measurements. Many acoustical experiments thus exhibit a dual nature. Part of the experiment is designed to decide upon a model and another part makes use of this model to interpret some characteristics of the sound field. As a rule in doing research one should try to use the relatively well understood standard properties of sound to determine the model. Sometimes, however, it is found that the standard methods are not accurate enough and then the experiment itself becomes a test of the model. Actually, since the essential validity of the wave equation for acoustics is unquestionable, one is practically forced to adopt the attitude that an acceptable interpretation of propagation measurements is a highly

PERCENT TRANSMITTANCE OF WATER IN INFRARED

Sample thicknesses are given in millimeters.

α is approximate absorption coefficient in cm^{-1} $(I = I_o\,e^{-\alpha x})$.

at wavelengths indicated.
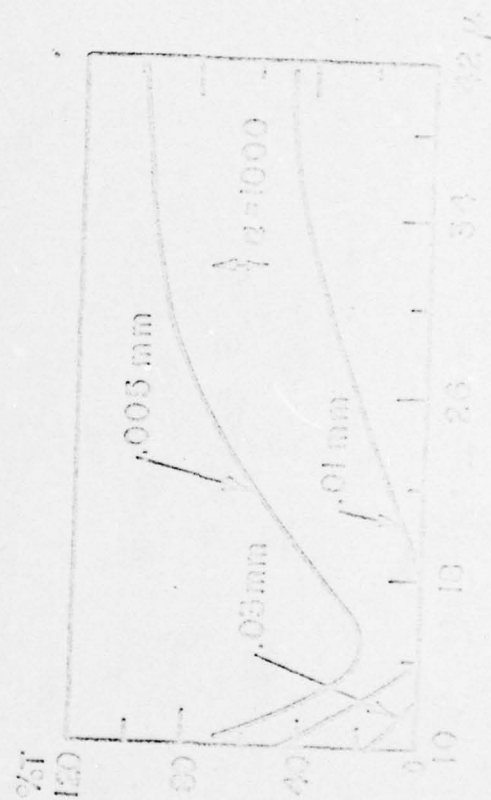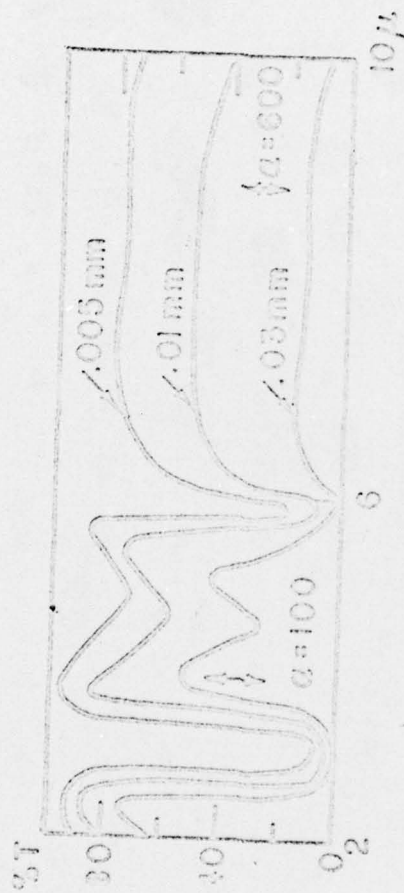
accurate, sophisticated method of determining the structure of the medium,

and, in particular, the variations of the velocity of sound.

To illustrate my point, I would like to review some of the factors

which determine acoustic propagation in the ocean. I will run through these

very quickly, as I am sure you are all reasonably familiar with them.

Acoustical propagation experiments have shown that the high frequency signals

have an attenuation constant proportional to approximately f^2. Since

this is expected from an approximate solution of the Stokes equation, it is

assumed that part of the intrinsic absorption is due to shear, dilational and

viscous losses. Attenuation caused by heat conduction in water is negligible.

Attenuation measurements in sea water reveal that salts dissolved in the

water are an additional cause of absorption. Measurements in artificial

sea water have shown that the magnesium sulfate is the principal cause, al-

though in sea water the magnesium sulfate salts constitute only about 4.7%

of the mass of the dissolved salts. The absorption due to chemical effects

is a relaxation mechanism and has a characteristic frequency and magnitude.

Absorption depends on pressure, temperature, and the electrolyte. Various

effects have been combined in the equation for the sound absorption of sea

water and the plane wave amplitude attenuation constant, which, according

to Marsh and Schulkin, is given by the rather complex formula shown in

the next slide.

The loss shown here is a loss due to bulk absorption in the medium by

internal relaxation processes. There are other ways one can lose energy

from acoustic beams and these come through absorption, dispersion from air

$$\alpha = \left(\frac{SAf_T f^2}{f_T^2 + f^2} + \frac{B f^2}{f_T} \right) \quad (1 - 6.54 \times 10^{-4} P) \text{ nepers/meter}$$

where:

S   is the salinity in parts per thousand

f_T is the temperature dependent relaxation frequency in kc at atmospheric pressure $= 21.9 \times 10^{\left[6 - 1520 / (T + 273) \right]}$

f   is the acoustic frequency in kc

A   is a constant (2.34×10^{-6}) for the ionic relaxation process in sea water

B   is nearly constant (3.38×10^{-6}) for the pure water viscosity mechanism.

P   is pressure in Kg/cm^2 or atmospheres

T   is the temperature in $^\circ C$

bubbles and particulate matter, and from boundary scattering. The energy

loss, as a result of reflection from a typical rough ocean surface, is also

a fairly complex function of oceanographic factors such as sea state, swell

height, wave height, period, etc. Indeed, one tends to get fairly complex

formulae to describe these effects. Such formulae as are available are

purely empirical relations that are really not well based theoretically, or even

experimentally. They represent approximations to a limited range of data.

In principle, the essence of underwater acoustical theory is described

by the simple scalar wave equation with a velocity of sound which can be a

function of one of several coordinates. Therefore, apart from the boundary

effects and viscous absorption effects, mentioned above, propagation depends

on the single parameter C, the velocity of sound. Until recently, most of

our knowledge concerning the dependence of C upon depth has been indirect

and was based upon experimentally measured values of the temperature, the

pressure, and the salinity. Of these three, the salinity is usually the least

important. For our purposes, it is sufficient to remember that salinity is

approximately a measure of the salts dissolved in the water. Typically, for

sea water it is of the order of 35 parts per thousand, and it is a quantity

which is routinely measured by oceanographers. Accurate determinations

of T require the use of special highly sensitive thermometers. The

common, very convenient instrument is, of course, the bathythermograph

which, when allowed to sink, gives a continuous record of T versus P,

which is accurate enough for most purposes. Relative temperature can be

read to almost .05 of a degree Centigrade corresponding to changes in the

velocity of sound to the order of .3 meter per second. As a rule, of

course, the use of bathythermographs is limited to the top few hundred meters

of the ocean. Given T, P, and S, the best equation for calculating C

appears to be a formula that was developed a few years ago by Wilson. This

equation fits the experimentally determined values of C to plus or minus .3

of a meter per second. We see that to first order the sound velocity increases

linearly with pressure and temperature. The direct measurement of the

velocity of sound in the ocean can now be accomplished by the use of veloci-

meters. These instruments, a fairly recent development as such things go,

measure the travel time of an acoustic pulse between two crystals spaced a

short distance apart. Commercially available units provide an accuracy of

about ± .3 meter a second. Their accuracy is essentially the same as that

of the lengthy, indirect method based on Wilson's equation. However, much

of our general information concerning the variability of C with latitude and

longitude will for some time to come be based upon oceanographic data of the

sort that resides in archival files. As of today, the accuracy of measurement

by indirect and direct methods is approximately the same, that is ± .3 of a

meter per second.

The horizontal variations of C, the velocity of sound, are quite weak

compared to the vertical changes. However, they are not insignificant. In

most range studies of acoustic propagation, the velocity of sound is often

treated as though it depends only on the vertical coordinate Z. In the case

$$C = 1449.22 + C_T + C_P + C_S + C_{STP}$$

where:

$$C_T = 4.6233T - 5.4585 \times 10^{-2}T^2 + 2.822 \times 10^{-4}T^3 - 5.07 \times 10^{-7}T^4,$$

$$C_P = 0.60518 \times 10^{-1}P + 1.0279 \times 10^{-5}P^2 + 3.451 \times 10^{-9}P^3 - 3.503 \times 10^{-12}P^4$$

$$C_S = 1.391 (S-35) - 7.8 \times 10^{-2} (S-35)^2, \text{ and}$$

$$C_{STP} = (S-35) (-1.197 \times 10^{-2} T + 2.61 \times 10^{-4}P - 1.96 \ .$$

$$\times 10^{-7}P^2 - 2.09 \times 10^{-6}PT) + P (-2.796 \times 10^{-4}T$$

$$+ 1.3302 \times 10^{-5}T^2 - 6.644 \times 10^{-8}T^3) + P (-2.391$$

$$\times 10^{-7}T + 9.286 \times 10^{-10}T^2) - 1.745 \times 10^{-10}P^3T.$$

where we wish to do acoustic propagation through regions of the ocean of 100
to a few thousand miles in extent, then we pass through rather significant and
striking variations in C. The simple approximation of one-dimensional depen-
dence on the vertical coordinate is no longer possible. Here, we find that an
examination of successive vertical velocity profiles reveals some remarkable
and striking things about the body of the ocean itself. That is, various changes
in velocity profiles which have been discovered have often been the first clue to
the existence of deep currents of differing water content. Typical mean C
versus D curves for deep water fall in several categories. The next slide
shows the three typical curves for the North Atlantic Ocean. The most
interesting profiles are those of the equatorial latitudes and moderate latitudes
which display a minimum at a depth of about 1200 or 1300 meters for moderate
latitudes and a little nearer to the surface in equatorial latitudes.

This type of profile is due to the effects of pressure and of temperature. At
first the temperature effect dominates. The decreasing temperature results
in a decreasing C. After a certain depth, however, the increase in hydrostatic
pressure gives an increasing C. Similar profiles characterize the South
Atlantic and the Pacific. In the latter case especially, the minimum C is
closer to the surface than in the North Atlantic. In polar latitudes the minimum
value of C is literally at the surface. It is obvious from elementary considera-
tions that sound may be trapped in such zones of minimum velocity and these are
acoustic wave guides or sound channels.

In general, if we had some Oceanographic Archangel to give us all
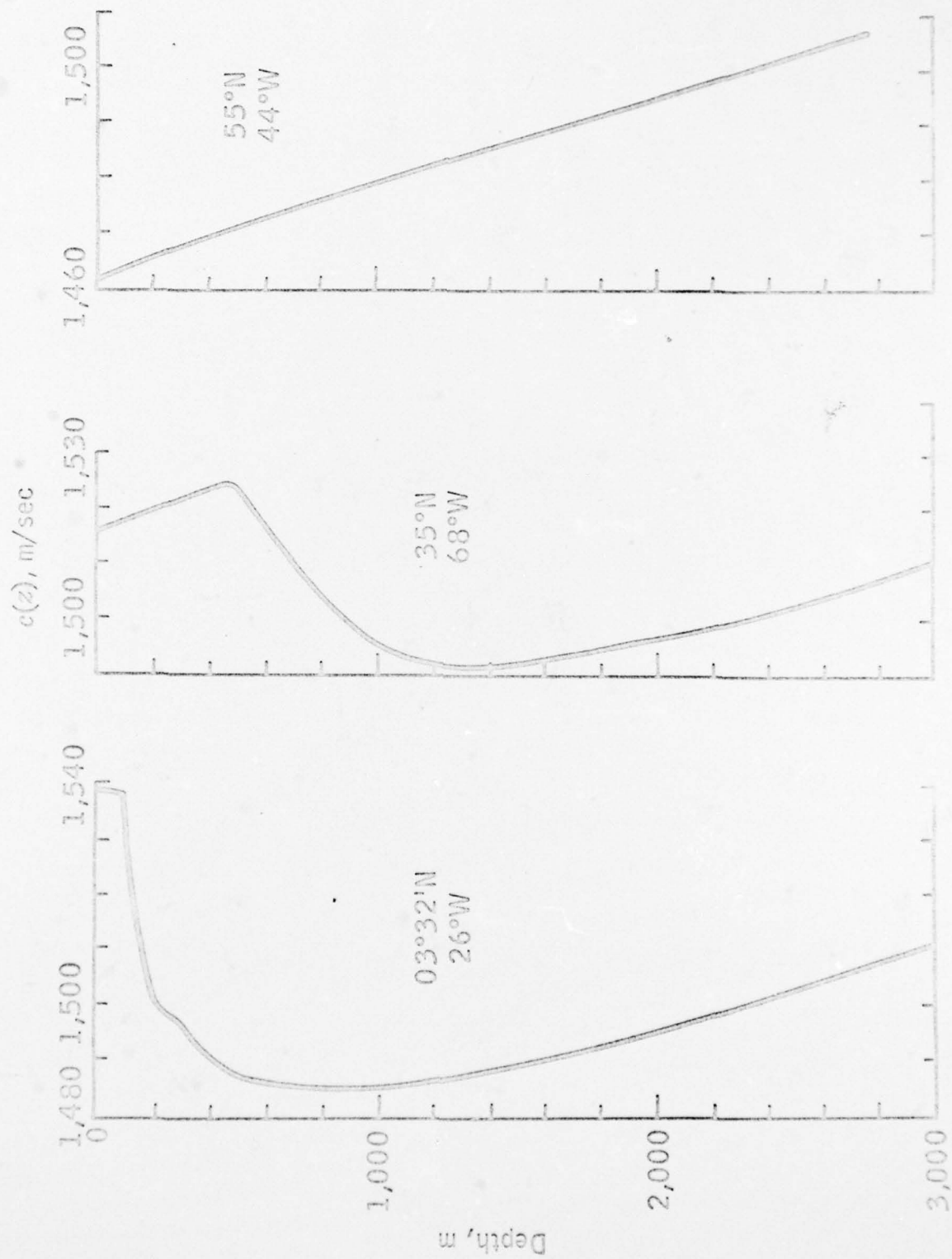
possible vertical velocity profiles between two points between which we wish to transmit acoustic energy, we would find that we really were not in position to make meaningful predictions as to the precise nature of acoustic propagation. My contention is that even if we had a relatively complete specification of all of the oceanographic factors in a given volume of ocean, we would still require a mathematical Archangel to give us the ability to predict the acoustic propagation. In lieu of Archangels, which are not very common these days, we tend to use computers. What one does is to use a grid of points and make essentially linear interpolations between the known profiles. One then attempts a numerical solution of the propagation problem for a medium in which there is a three-dimensional variation of the velocity of sound. Such calculations are at present of very questionable merit. They are extremely long, extremely tedious, and the effects of cumulative errors in such massive calculations may, indeed, be such as to completely vitiate the results.

We finally come to the somewhat melancholy conclusion that whereas we instinctively feel that a knowledge of oceanographic factors is essential, we find that the acoustician cannot use them as well as we might imagine. On the other hand, we have the fortunate and very happy situation that when we have properly designed acoustic tools at our disposal the oceanographer can, indeed, use acoustics as a valuable adjunct to his study of his ocean. In fact, the oceanographer finds that it is the only tool which will eventually allow him to understand and comprehend the complexities of his medium.